APPENDIX D

ESTUARINE SEDIMENTATION ANALYSIS

D-1. Sediment Sources. Identification of the sources of sediment can be a key factor in problem solving. Original sources are upland, internal, and coastal. Section D-11, subparagraphs c-e, describe the evaluation of transport routes that comprise immediate (local) sources.

a. Upland. The predominant source usually is from surface erosion of lands draining into the water body, but sediments eroded from riverbanks also contribute. In some cases, flows from the upland may carry significant quantities of organic material.

b. Internal. Currents and waves resuspend sediments from bed and banks within the estuary, and aeolian transport introduces sediment in a more direct manner. In biologically active areas, organic production within marshes and the main estuarial water body itself can significantly enhance total suspended solids and shoal volumes (Kranck 1979). Wastes can add considerably to organic loading.

c. Coastal. Close to the estuarial mouth, the sediment is often of marine origin. In areas where the open seacoasts are sandy, it is common to find the bed in the mouth or entrance channel to consist predominantly of sand. Landward of the entrance the grain size decreases and the fraction of fine-grained material tends to increase (Mehta and Jones 1977). In some estuaries, such as the Mississippi or the Amazon Rivers, where sediment supply from upstream sources has been relatively high on a geologic time scale, the offshore ebb delta is laden with deep layers of fine-grained material (Gibbs 1977; Wells 1983). Thus density- and tide-driven flows can transport some of the fine-grained ebb deltaic deposits (resuspended during flood flows coupled, oftentimes, with offshore wave activity) upstream through the channel. The material is then redeposited in reaches where the currents are too weak to transport the material further or at the nodal point for bottom flow predominance (Partheniades 1966).

D-2. Sediment Classification. For engineering purposes, sediments are customarily classified primarily according to particle size. Sediment of size greater than about 0.074 mm (No. 200 seive size) is considered to be coarse sediments, and less than this size to be fine-grained sediments. The terms "coarse" and "fine" are relative to fine-grained sedimentation and not the American Society for Testing and Materials (ASTM) class. The boundary between cohesive and cohesionless sediment is not clearly defined and generally varies with the type of material. Cohesion generally increases with decreasing particle size. Thus clays (particle size <0.005 mm) are much more cohesive than silts (0.005 to 0.074 mm), and, in fact, cohesion in natural muds is due primarily to the presence of clay-sized sediment. Silt-sized material (particularly of size larger than ~0.02 mm) is only weakly cohesive, but when in combination with a sizeable fraction (by weight) of clayey sediment, constitutes a sediment which, in the flocculated state, exhibits a behavior characteristic of cohesive sediments.

a. Muds. Estuarial muds are typically composed of a wide range of materials including clay and nonclay minerals in the clay- and silt-size ranges, organic matter, and sometimes small quantities of very fine sand. Muds often occur in the presence of coarse sand, shell, and other macrosized detritus.

b. Size. The particle size distribution of coarse materials is easily determined by sieve analysis, and reported either in terms of diameter d or in ϕ units (i.e., as $-\log_2 d$). It is most common to characterize the size distribution by the median (by weight) size and the corresponding variance, standard deviation, uniformity coefficient, or sorting coefficient (Terzaghi and Peck 1966; Vanoni 1975; and US Army Engineer Waterways Experiment Station 1984). Skewness and kurtosis, particularly the latter, are less commonly used mainly because the degree of acceptable accuracy in typical sediment transport calculations does not warrant the use of these size-distribution characterizing parameters. However, they can be useful indicators of sediment sorting in studies meant to examine spatial sorting trends, e.g., of the bottom sediment with distance along the estuary.

c. Settling Velocity. The customary practice of reporting grain-size distribution has arisen out of the simplicity of sieve analysis as a measuring technique. It must, however, be noted that the key transport-related parameter is the settling velocity, which, unfortunately, does not bear a unique relationship with particle size. Laboratory settling columns can be used to measure settling velocity distribution, which may be considered as a very useful property for sediment classification (Channon 1971; Vanoni 1975).

d. Cohesive Treatment. Cohesive sediments are deflocculated, or dispersed, by removing salts from the fluid through repeated washing with salt-free water and adding a dispersing agent such as sodium-hexametaphosphate prior to particle size determination. Standard hydrometer or pipette methods are used to determine the dispersed particle size distribution (ASTM 1964). The original sample should not be dried before determining the size distribution, inasmuch as prior drying prevents the material from dispersing adequately (Krone 1962).

e. Deflocculation. Cohesive sediment size distribution obtained without dispersion will be that of the flocculated material, which bears no unique relationship to that of the dispersed material. The floc size distribution yields a qualitative indication of sediment behavior in the prototype.

f. Settling Tests. A convenient laboratory procedure for obtaining the settling velocity of flocculated sediment consists of settling tests in a column. Sediment samples are withdrawn at various elevations and different times after test initiation (Owen 1976; Vanoni 1975; Teeter and Pankow 1989a). This procedure yields an empirical relationship between the median settling velocity and suspended sediment concentration, which is unique to the type of sediment-fluid mixture used (see also section D-6 and D-7). It is preferable to use the actual estuarial fluid in these tests. If conditions permit, field tests are recommended (Owen 1971; Teeter and Pankow 1989a).

D-3. Coarse Sediment Transport. Coarse-grained sediment includes material larger than about 0.074 mm (74 μm), the most common sediment being sand, although some estuarial beds are laden wholly with coarser material including shells and gravel (Kirby 1969).

a. With reference to sand transport, the estuarial mouth or tidal entrance can be in many cases conveniently treated as a geomorphologic unit separately from the remainder of the estuary. Sediment transport is influenced strongly by the hydrodynamics of flood and ebb flows within the entrance channel and over the flood and ebb shoals adjacent to the channel (Mehta and Joshi 1984). In the ebb shoal area in the sea, tidal flows interact with crosscurrent generated typically by wave-driven alongshore flows. Penetration of waves from the sea into the entrance channel, particularly during flood, can have a marked effect on the rate of sediment transport and the distribution of bottom sediment (Bruun 1978; O'Brien 1969).

b. The application of sediment transport formula developed for unidirectional flows is usually suitable to tide-dominated oscillatory flows because the tidal frequency is low, and tidal currents may be considered to be "piecewise" steady. Differences tend to arise due mainly to three causes:

(1) The complexity of flow distribution resulting from salinity effects.

(2) The condition of slack water and flow reversal following slack.

(3) The dependence of bed forms and associated bed resistance on the stage of tide and the direction of flow.

c. The total rate of sediment transport is the sum of contributions from bed load and suspended load. Bed load rate varies with n^{th} power of the excess shear stress. Values of the exponent n have been found to vary from less than 1.5 to as high as 3 (Vanoni 1975; Yang 1972). Generally, for the coarse beds the exponent is nearer 1.5; for fine material the exponent is nearer 3.

d. Bed material load is a term which is sometimes confused with bed load. Bed material load means that portion of the total load represented in the bed and includes bed load and suspended bed material. The remainder is wash load, typically fine-grained and, unlike bed material load, it is believed to be independent (uncorrelated) of flow condition. Bed load is that material moving on or near the bed. The stochastic nature of nearbed turbulence and associated sediment transport indicates that a given material can behave either as wash load or as bed material load, depending upon the properties of the material and the flow condition (Partheniades 1966).

e. Whether a sediment under a given flow condition behaves as bed load or as suspended bed material load depends on the relationship between the entrainment function, Θ, and the dimensionless grain size, d_{gr}, as illustrated in Figure D-1 (Ackers 1972). Here

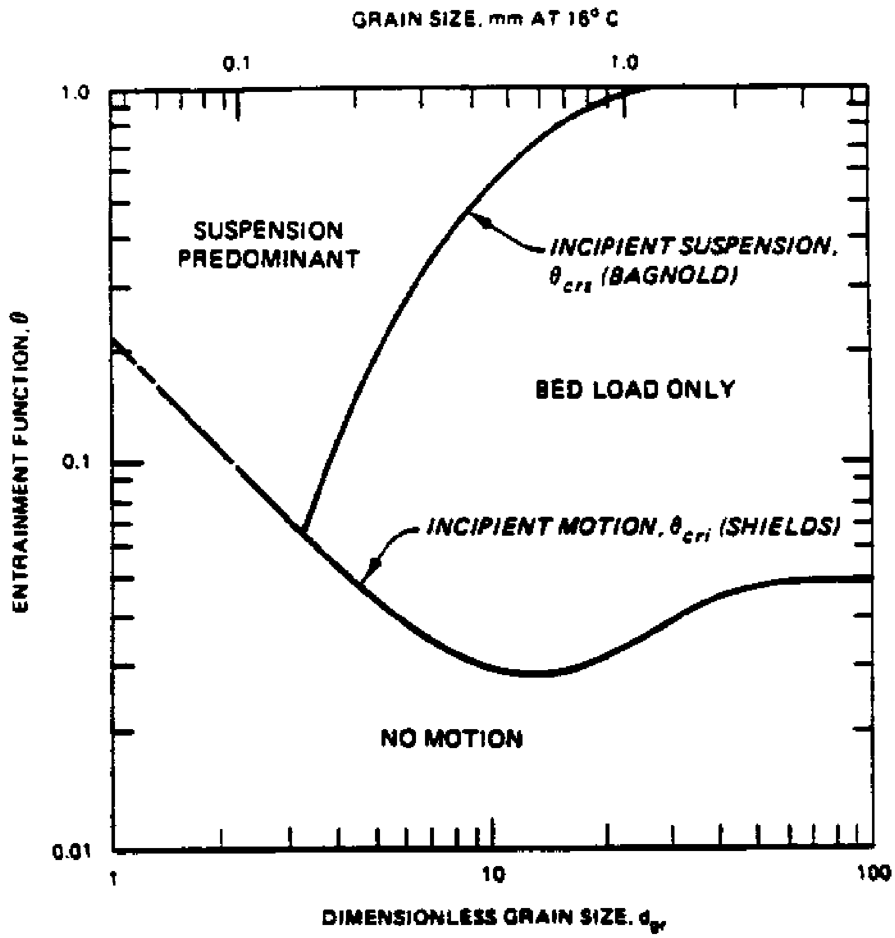

Figure D-1. Relationship between entrainment function, Θ, and dimensionless grain size, d_{gr} (after Ackers 1972)

$$\Theta = \frac{\tau_b}{(\gamma_s - \gamma)d} \tag{D-1}$$

$$d_{gr} = d\left\{g\left[\frac{(\gamma_s - \gamma)}{\gamma \nu^2}\right]\right\}^{1/3} \tag{D-2}$$

where

τ_b = bed shear stress
γ_s = unit weight of the sediment
γ = unit weight of water
d = grain size
g = acceleration due to gravity
ν = kinematic viscosity of the fluid

In Figure D-1, the lower curve corresponds to Shields' relationship which defines a critical value Θ_{cri} of the entrainment function whose magnitude depends on the roughness Bagnold's number, $u_* d/\nu$ (where u_* is the friction velocity) (Shields 1936). At values below Θ_{cri} there is negligible motion of bed material. The upper curve corresponds to Bagnold's (1966) relationship which defines another critical value, Θ_{crs}. Above this value of Θ the sediment is transported predominantly in suspension. Between the two curves is the domain in which bed-load transport occurs. By virtue of the nature of these two curves, which intersect at a point corresponding to $d_{gr} \simeq 3.2$, for particle sizes that correspond to d_{gr} smaller than this value, transport is predominantly in suspension. Indeed for particles of sizes less than about 0.04-0.06 mm, bed-load transport does not occur (Mehta and Partheniades 1975).

f. The contribution of suspended load relative to bed load (in total load) depends on the grain size, the flow regime, and the estuarial morphology. In most estuaries, bed load is a small fraction of the total sediment load.

g. The rate of supply of "new" sediment from the river varies widely from one estuary to another, and, in a given estuary, there is usually a strong seasonal dependence as well (Krone 1979). Normally, however, the oscillatory, "to and fro," tide-controlled transport is orders of magnitude higher than the net (incoming minus outgoing) input of sediment. By the same token, the residence time of incoming sediment is usually very long and, in some cases the material is "permanently" deposited in the estuarial bed. In the long term, such factors as changes in the upstream discharge hydrograph and sediment supply rates, morphologic changes within the estuary, sea level change, and eustatic effects will alter the sediment transport regime (Dyer 1973; McDowell and O'Connor 1977). Generally estuaries import sediment and are filling with sediment.

h. Closure or tidal choking is a potential problem at sandy entrances where the strength of flow is insufficient to scour the bed, with the result that littoral drift is deposited in the mouth, the depths become shallow, and the entrance eventually closes (Bruun 1978). As a result of runoff, however, closure will be restricted to times of very low freshwater outflows, since at other times a hydrostatic head will build up sufficiently to cause an eventual breakthrough at the site of sand deposition in the mouth. When the mouth is closed, the estuary changes into a lagoon or lake of brackish water. There is no access to the sea, and water quality degradation often occurs. Training walls or jetties and dredging between the jetties coupled, sometimes, with a system for bypassing sand from the updrift beach to the downdrift beach can be used to keep entrances open (Bruun 1978).

i. Sand in transport can form waves. Sand waves occur where flows are strong and sediment supply sufficiently large. Sand waves are described as either dunes (migrate downstream) or as antidunes (migrate upstream). Dunes are by far the most common sand waves observed in rivers and estuaries. In estuaries they can grow to heights of 10 to 20 feet with wavelengths of hundreds of feet, and can impede navigation.

D-4. Cohesive Sediment Transport. Cohesion greatly influences the behavior of sediment materials and their transport processes. Cohesion results from interparticle electrochemical forces, which become increasingly important relative to the gravitational force with decreasing particle size below 0.04 mm. Clays, which have sizes less than 0.005 mm, are particularly cohesive.

a. At moderate suspended solids concentrations, depositing cohesive aggregates stick to the bed, and as they accumulate, buried aggregates are consolidated by the weight of the overburden. The strength of a deposit therefore increases with depth below its surface. The shear strength of a deposit must be overcome by the hydraulic shear stress before erosion begins. At shear stresses immediately above the critical stress for breaking of individual particle bonds, "surface" or "particle" erosion occurs. When the applied hydraulic stress is increased to the level where turbulent eddies impinge on and break small elements from the bed, "significant" erosion occurs. Significant erosion rates are much higher than particle erosion rates. When the applied hydraulic stress is increased to the level where it exceeds the bulk shear strength of a deposit, "mass" or "bulk" erosion occurs. This latter type of erosion instantaneously suspends bed material to the depth where the deposit strength equals the applied stress.

b. Particle cohesion requires interparticle collision. There are three basic mechanisms for collision: Brownian motion, flow shear due to turbulence, and settling of particles at different speeds, or differential settling (Hunt 1980). Out of these, shearing in the fluid column, which is prevalent throughout the tidal cycle except at slack water, produces the strongest interparticle bonds. Brownian motion is important in high-density suspensions, whereas at times of slack water as well as during the period immediately preceding slack water when rapid settling is occurring, differential settling plays an important role (Krone 1972).

c. At very low concentrations, e.g. ~100 mg/ℓ or less, interparticle collision frequency is restricted by the dearth of particles in suspension. Particles settle more or less independently, and the settling velocity shows no significant dependence on concentration. At higher concentrations, up to ~3,000-5,000 mg/ℓ, aggregation is enhanced with increasing concentration, and the settling velocity varies with m^{th} power of concentration, with m ranging from ~0.8 to 2, with a typical value of 1.3. At even higher concentrations, particularly in excess of ~10,000 mg/ℓ, the settling velocity begins to decrease with increasing concentration as aggregates form a continuous network through which pore water must escape upward for settling to occur. This is referred to as hindered or zone settling. The term fluid mud is often used to describe a high-concentration (>10,000 mg/ℓ) suspension that characteristically exhibits the hindered settling behavior (Krone 1962).

d. Aggregates of sediment in the clay- and silt-size range typically behave as bed material load (however not as bed load), while very fine material, e.g., derived from biogenic sources, often behaves as wash load, not being represented in the bed.

e. Inasmuch as cohesive aggregate properties (e.g., size, density, and shear strength) depend on the type of sediment-fluid mixture as well as the flow condition itself, particle size has a different meaning here than in the case of cohesionless sediment, since aggregate size is not an easily characterized quantity. The critical shear stress for erosion, or more accurately, the cohesive bed shear strength with respect to erosion, depends on the mode of formation and degree of consolidation of the bed (Mehta et al. 1982). Consequently, Shields' (1936) relationship between the critical value of the entrainment function Θ_{cri} and the roughness Reynolds number, is not applicable to particles of sizes less than ~40 μm (see also Figure D-1 and Paragraph D-3). It becomes essential to conduct laboratory erosion tests to evaluate the bed shear strength for a given mud-fluid mixture (Mehta et al. 1982; Parchure 1984).

f. The process of cohesive sediment deposition and erosion are interlinked through bed consolidation. Rates of deposition and erosion in turn determine the rate of horizontal transport in suspension. In a tidal estuary, these processes are characteristically cyclic in nature; their interrelationship is schematized in Figure D-2 (Mehta et al. 1982). Suspension transport interacts with the bed through tide-controlled, time-dependent, deposition-consolidation-erosion process. The thickness and density of the deposit

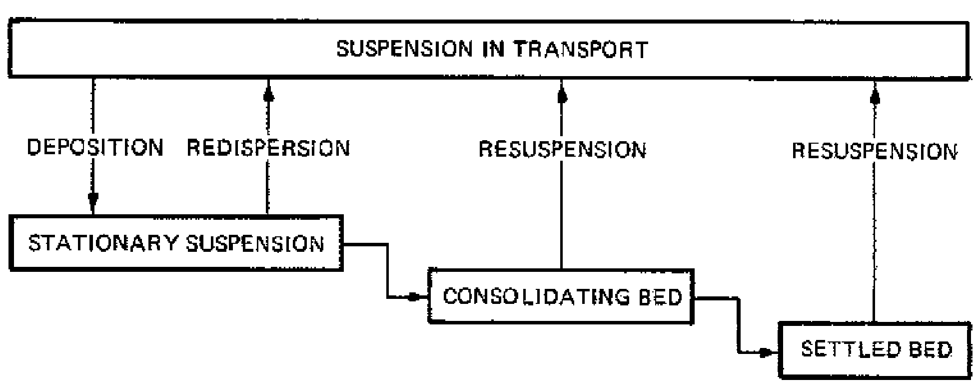

Figure D-2. Schematic representation of the physical states of cohesive sediment in estuarial waters (from Mehta et al. 1982) respond to rates of deposition and erosion, and the deposit is continually undergoing consolidation. The "bed" level changes throughout the tidal cycle; and in most cases, precise prediction of bed level changes in an environment where both deposition and erosion occur over a tidal cycle requires numerical modeling of the governing equations of continuity, momentum, and mass transport (Ariathurai and Krone 1976; Hayter and Mehta 1984). In Figure D-2 it is indicated that settling of sediment (during times of decelerating flows and at slack water) results in a stationary suspension at the bottom. In this type of high-concentration suspension, hindered settling occurs; and there is, by definition, no horizontal transport (Parker and Kirby 1982). The deposit then forms a bed through settling and consolidation. During consolidation (and gelling), upward escape of the pore water occurs, the bed density increases, and physicochemical changes occur within the bed as the deposited aggregates are crushed slowly under overburden. A settled or fully consolidated bed eventually results. In such a bed, bed properties do not alter with time. Relatively thin deposits, on the order of a few centimetres thickness, consolidate in a week or two, but thick deposits may remain underconsolidated for months or even years.

D-5. Impact of Flow and Geometry. Flow and sedimentary boundary conditions are critically important in governing estuarial sediment transport. At the mouth, tidal forcing is determined by the open coast tide characteristics as well as the geometry of the mouth itself. Thus, for instance, the type of sediment in the mouth area is contingent upon the properties of the sediment discharged through the river as well as the nature of open beach deposits. At the upstream end, beyond the influence of tides, the river discharge hydrograph and sediment inflow are key factors. Within the estuarial reach, runoff, direct precipitation, and bank erosion by currents and waves can be significant factors that contribute to the overall sedimentary regime.

a. Currents broadly divide the estuarial sedimentary environment into three categories: predominantly erosional, predominantly depositional, and mixed. Deposition-dominated environments include flood and ebb deltas near the mouth, shoal areas within the estuary including natural and dredged navigation channels, and basins including ports and marinas.

b. Sites where erosion is predominant tend to be localized in comparison with sites of deposition, although sometimes large previously deposited shoals disintegrate in the absence of sediment supply.

c. In a mixed deposition/erosion environment in which net scour or shoaling is small, as would occur if the regime were in a state of "live bed" equilibrium, the rates of deposition and erosion can be high individually, and these would cause significant "to and fro" transport of sediment during a tidal cycle. On the other hand, in mild to moderate tidal environments, the rates of sediment transport under "normal" conditions may be small, but can be enhanced by as much as two to three orders of magnitude during episodic events including storms. In such an environment, sediment transport is not wholly tide-controlled, and it becomes essential to obtain long-term measurements of the rates of sediment transport in order to characterize seasonal and episodic influences on the physical regime.

d. The role of waves superimposed on tidal currents can be quite important. Shallow- and intermediate-depth water waves provide a critically important mechanism for incipient motion, resuspension of bottom sediment, and the formation of fluid mud layers. The sediment is then advected by the tidal currents. The often observed measurable rise in sediment transport rates during storms is quite often due mainly to bottom erosion by wave-induced oscillatory velocities since tidal velocities do not always increase significantly during storms unless a storm-induced surge occurs. Wave breaking at the banks can also cause a measurable increase in sediment concentrations and subsequent transport rates.

e. Aeolian transport is usually ignored in typical estuarial transport calculations. In certain areas, such as small basins, wind-blown material can form a significant fraction of the total deposit, particularly where sediment transport rates in the water body are not high. The degree of susceptibility of the surrounding terrain to wind-induced erosion will be a contributing factor independent of tides. However, exposure of terrain is somewhat dependent on tides; e.g., for large-amplitude tides, a greater length of beach is exposed to wind effects during low water.

f. The rise of sea level relative to land has contributed to measurable bank erosion in some estuaries and should be considered when comparing bathymetric surveys taken at widely different times (Krone 1979).

g. The impact of estuarial geometry on sediment transport is associated with the effect of geometry on flows that transport sediment. For example, it is quite common to find relatively well-defined flood- and ebbdominated channels with consequent implications for the direction of sediment transport. Furthermore, deep, dredged channels often are natural sites for sedimentation as are basins constructed along estuarial banks. Until recent times, structural means to train or control estuarial flows or shoaling/scour were often employed as and when necessary, sometimes without regard to its implications on overall estuarial stability. In some estuaries, e.g., the Mersey in England, this has resulted in severe problems for navigation and berthing (Bruun 1978). Diversion of tributary flows for agricultural or urban uses can also have deleterious effects, both with respect to sedimentation as well as water quality (McDowell and O'Connor 1977).

h. The null zone is often the area of highest concentrations of suspended particulates and rapid sediment accumulation (shoaling) (Inglis and Allen 1957). Several processes account for this. Sediments that settle into the lower part of the water column are transported upstream by tidal-residual circulation to the null zone. Sediments scoured from the bottom and transported on the flood tide and then deposited on the ebb tide phase are tidally pumped toward the null zone. At the limit of salinity intrusion (usually a relatively short distance upstream from the null zone), scour can occur on the ebb tide phase, encouraged by freshwater deflocculation of consolidated muds.

i. A constriction within a tidal flow will cause a near-bottom tidal-residual convergence zone that can trap sediments. Constrictions have been associated with shoal areas, as an example, inner and outer shoals associated with arrowhead jetties.

D-6. Sediment Characterization and Analysis. Characterization provides the basic information for identifying transport processes. Characterization tests for coarse- or fine-grained sediment depend on the nature of sediment. It is common to find sediment from a site to consist of a range of materials from coarse size to clay size. In such a case it usually becomes necessary to separate the coarse and fine fractions and analyze them separately.

a. For coarse sediment it is typically useful to evaluate particle size distribution or, preferably, settling velocity distribution; material density and bed porosity; and, sometimes, the angle of repose.

b. Size distribution for coarse sediments is customarily obtained through sieve analysis in terms of selected sieve sizes. It is preferable to characterize sediment by its settling velocity, which is more basic to sediment transport. Since the drag coefficient of a particle in the fluid varies, in general, with particle size, shape, and density, there is no unique relationship between size and settling velocity; and it is somewhat speculative to relate particle size to settling velocity through plots or nomograms in which the particle shape must typically be assumed. Details on particle size and settling velocity measurements as well as material density and bed porosity are found elsewhere (Vanoni 1975). The angle of repose is a basic property associated with bank stability as well as incipient grain movement (Lane 1955; Mehta and Christensen 1983).

c. For cohesive sediment, the problem of characterization is more complex than that for coarse-grained material, because sediment aggregate properties depend on the type of sediment, the fluid, and the flow condition itself.

d. For characterizing the fine-grained sediment, it is recommended that the following be specified:

(1) Grain size distribution of dispersed sediment using, for example, the standard hydrometer test (ASTM 1964).

(2) The relationship between the median settling velocity and the suspension concentration of the flocculated sediment (Owen 1976).

(3) Clay and nonclay mineralogical composition through X-ray diffraction analysis (Grim 1968).

(4) Organic content (Jackson 1958).

(5) The cation exchange capacity, which is a measure of the degree of cohesion of the clay (Grim 1968).

e. For characterizing fluid in regard to fine-grained sediment, it is recommended that the following conditions be specified:

(1) Concentrations of important cations (e.g., sodium (Na^+), calcium (Ca^{++}), and magnesium (mg^{++})) and anions (e.g., chlorine (Cl^-) and sulfate (SO_4^{--})).

(2) Total salt concentration.

(3) pH.

(4) Fluid temperature during measurements as well as in laboratory experiments for determining the rates of erosion and deposition.

Items (1), (2), and (3) can be determined through standardized chemical analysis procedures.

f. Recognizing that sodium, calcium, and magnesium are three comparatively more abundant and influential cations, the sodium adsorption ratio (SAR) is found to be a convenient parameter for characterizing the influence of fluid chemistry on cohesive sediment transport behavior. This parameter is defined as

$$SAR = \frac{[Na^+]}{\left\{\dfrac{[Ca^{++}] + [Mg^{++}]}{2}\right\}^{1/2}} \qquad \text{(D-3)}$$

where [ ] indicates ionic concentration in milliequivalents per liter. SAR is essentially a measure of the degree of abundance of sodium relative to calcium and magnesium.

g. Inasmuch as consolidation increases bed density, it is important to obtain representative in situ cores for determining the depth-distribution of the density (bulk and dry) of the bed. This information enables a conversion between deposition and erosion of sediment mass per unit time and the corresponding changes in the suspension concentration (mass per unit volume), and gages the hydraulic shear strength of the sediments.

h. In studies in which dissipation of fluid energy within the bed plays an important role, e.g., wave-mud interaction, it is essential to evaluate the rheological properties, the most important one being the viscosity, which has been found to be related to sediment concentration in an approximate manner (Krone 1963). Muds typically exhibit a non-Newtonian rheology. Thus it becomes necessary to specify parameters in addition to viscosity. Most commonly this includes the Bingham yield stress, for a comparatively simplified rheological description. The dynamic behavior of muds under wave-induced loading suggest a visco-elastic response.

i. The characterization of sediment is necessary to aid in the identification of transport and deposition processes. Preplanning for specific project data colletion programs is essential so that the proper type, quantity, and data analysis can be conducted. The preceding and following paragraphs describe various field tests and sediment analyses, which may or may not be required. The amount and type of data and required procedures and tests should be determined during the project planning stage. Too much or too little data could be costly and detrimental to the project. These chapters and appendices provide general guidance; specific guidance can be found in Appendix A or through the Hydraulics Laboratory, WES.

D-7. Transport Parameters. The movement of sediment is sensitive to flow speed and direction, and it is particularly important to characterize the flow regime including the influences of salinity, geometry, and wind and related factors for a comprehensive evaluation of the overall sediment transport regime. Errors in correctly specifying the flow field will result in corresponding discrepancies in the prediction of the rate and direction of sediment transport. In a water body with large longitudinal and lateral dimensions, inadequate specification, for instance, of the flow direction, can lead to significant errors in the prediction of sites of sedimentation, particularly if the sediment is fine-grained, as a result of the relatively long distances over which the sediment is advected over each flood and ebb.

a. Particle settling velocity is both an important sediment characterizing parameter as well as deposition-related parameter. The critical shear stress is the important erosion-related parameter. Field and laboratory procedures for evaluating these and associated parameters, where cohesionless sediment transport is concerned, are well-documented in literature (Owen 1970; Vanoni 1975). It must be recognized that, as a result of estuarial variability, it is essential to obtain adequate prototype measurements for the rates of sediment transport in each site-specific investigation. Use of sediment transport formulas without adequate calibration of the formulas may lead to major errors in transport rate prediction.

b. Cohesive sediment transport processes that require parametric characterization include settling and deposition, consolidation, and erosion (Teeter, Hodges, and Coleman 1987). This information, coupled with formulations for the diffusion coefficients for sediment in suspension, forms the basis for predictive mathematical modeling for evaluating the temporal and spatial description of the suspended sediment concentration, given the flow field and boundary conditions (Hayter and Mehta 1984).

c. Settling is principally characterized by the relationship between the median settling velocity and suspension concentration:

$$W_s = f\ (C) \qquad \text{(D-4)}$$

where W_s is the median (by weight) settling velocity and C is the suspension concentration (dry mass of sediment per unit volume of suspension). There are basically four procedures for evaluating this relationship, each under a specific set of conditions and, therefore, yielding results which are peculiar to those conditions. These procedures are as follows:

(1) Tests in a laboratory settling column. This involves starting with an initial, flocculated suspension of known concentration in a well-shaken column, allowing the material to settle subsequently under quiescent conditions, and sampling the suspension at selected elevations and time (ASTM 1964; Hunt 1980; Krone 1962).

(2) Highly specialized tests in an appropriate laboratory flume. Sediment is initially suspended at a high flow velocity and then allowed to deposit at reduced velocity. Suspension concentration is sampled at selected times after deposition begins. The rate of aggregation is high, particularly in the beginning, provided the suspension concentration is greater than 1,000 mg/ℓ (Krone 1962; Mehta and Partheniades 1975; Teeter and Pankow 1989b).

(3) Use of in situ settling tube. This tube, designed originally by Owen (1971), allows for onsite measurements. The "Owen tube" is lowered from a boat for collecting the suspension sample. In water it is held in a horizontal horizontal attitude. When drawn out of water, it pivots vertically, and the sediment within the suspension begins to settle. Subsamples of the suspension are withdrawn at selected times from the tube, and the settling velocity determined in a manner similar to that using a laboratory settling column. By performing the settling test almost immediately following sample withdrawal from the water body, the aggregates are presumed to remain unaltered in composition. Measurements obtained through this procedure are sometimes found to yield settling velocities as much as an order of magnitude larger when compared with corresponding measurements in laboratory settling columns. Relationships obtained between settling velocity and concentration determined from field tests also include variability in sediment characteristics caused by variations in such variables as flow and inflow conditions and water chemistry (Teeter and Pankow 1989a).

(4) Comparison of measured suspended sediment concentration profiles (depth-concentration variation) with analytic prediction. The unknown in the latter is the settling velocity, which can be evaluated by matching the measured and theoretical profiles. In some relatively "well-behaved" situations, this procedure results in acceptable values of the settling velocity (Mehta et al. 1982; O’Connor and Tuxford 1980).

d. For prototype application, the use of the in situ tube is the preferred method of measurement of settling velocity. Extensive measurements of this nature have, for instance, been obtained in the Thames Estuary in England (Burt and Stevenson 1983). Comparison between measured and theoretical concentration profiles, where feasible, can yield realistic values of the settling velocity (Mehta et al. 1982). Laboratory flume or settling column tests should be used for supplementary and/or confirmatory evidence. A major difference between flume and settling column test results is that, while deposition occurs under continued aggregation in the flume under flow, settling in a column occurs in the absence of shearing rates and aggregation proceeds very slowly.

e. The rate of deposition depends on the rate at which the fraction of the settling sediment deposits, the remainder consisting of aggregates that break up near the bed under the action of bed shear stress and/or are re-entrained. The reentrained pieces may reaggregate and settle again, some of those will deposit, and so on. Deposition is expressed as

$$\frac{dm}{dt} = - W_s\bar{C}\left(1 - \frac{\tau_b}{\tau_{cd}}\right); \ \tau_b < \tau_{cd} \qquad \text{(D-5)}$$

where

m = mass of suspended sediment per unit bed area over the depth of flow
t = time
C = depth-averaged suspension concentration
τ_b = bed shear stress
τ_{cd} = critical shear stress below which all initially suspended sediment deposits eventually

For a particular sediment, τ_{cd} can be evaluated from laboratory flume experiments (Krone 1962). For a uniform (narrow primary particle size distribution) sediment, single values of W_s and τ_{cd} will suffice. For a graded sediment (e.g., a typical mud with a relatively wide range of sizes from coarse silt to fine clay), W_s and τ_{cd} will have corresponding wide ranges. These can be determined by fractionating the sediment into two or three parts in terms of size, and evaluating W_s and τ_{cd} for each fraction through flume deposition tests. On the other hand, the unfractionated sediment sediment will exhibit a composite behavior whereby above a certain characteristic value of the bed shear stress (Teeter and Pankow 1989b), a fraction of the total initially suspended sediment will not deposit, even in the long run (Mehta and Partheniades 1975), as a consequence of the occurrence of ranges of W_s and τ_{cd}, instead of single values of these two parameters.

f. Consolidation of freshly deposited mud is accompanied by release of excess pore pressure, decrease in total bed thickness, corresponding increase in bed density and physicochemical changes associated with interparticle bonds, including gelling. Following bed formation, gelling is complete in about a day (Krone 1983).

g. From the perspective of estuarial sediment transport, the decrease in bed depth accompanying consolidation is not always of critical importance. Of much greater importance are density increase and physicochemical changes, because these in turn control corresponding changes in the bed shear strength with respect to erosion (Mehta et al. 1982). For relatively thin beds, on the order of a few centimetres in thickness, consolidation, in the absence of additional deposition, is practically complete in a period on the order of one or two weeks, and the rate of bed deformation becomes small in comparison with the rate immediately following bed formation. Bed properties including density and erosional shear strength become nearly invariant with further passage of time and a stabilized, or settled, bed (Figure D-2) results.

h. Investigators have found an approximate relationship between the bed resistance to erosion and bed density, specific to the type of sediment and fluid used (Migniot 1968; Owen 1971; Thorn and Parsons 1980; Teeter 1987). Given τ_s the critical shear stress for erosion and ρ, the dry density, the relationship is of the form

$$\tau_s = \alpha\rho^\beta \tag{D-6}$$

where α and β must be determined experimentally.

i. The rate of surface erosion is obtained from

$$\frac{dm}{dt} = M\left(\frac{\tau_b - \tau_s}{\tau_s}\right); \quad \tau_b > \tau_s \tag{D-7}$$

where M is an empirical erosion rate constant (Ariathurai and Arulanandan 1978; Mehta et al. 1982). Note that excess shear stress, $\tau_b - \tau_s$, is an important rate-determining parameter. In general, M and τ_s must be evaluated through erosion experiments in flumes. It should be noted that τ_s changes with depth of erosion into the bed. Mass erosion to the depth of the bed where shear strength equals the applied stress occurs with increasing stress.

D-8. <u>Causes of Sediment Deposition.</u> As evident from Equation D-5, the rate of sediment mass deposition dm/dt increases with increasing settling velocity W_s and with suspension concentration C, and decreases with increasing bed shear stress τ_b, given τ_{cd}. Likewise, Equation D-7 indicates that the rate of sediment erosion increases with increasing τ_b for given magnitudes of τ_s and M. This means the instantaneous value of the concentration C (obtained by integrating the rate of erosion over the duration of erosion) increases with τ_b as well. It follows from Equation D-5 that the mass of sediment deposited depends on the availability of entrained sediment, its settling velocity, and flow condition as reflected primarily in the bed shear stress. This type of reasoning is generally applicable to cohesive as well as cohesionless sediment.

a. A deposition-dominated environment is characterized by a region of relatively low bed shear stress in which the rate of supply of sediment to the bed well exceeds the rate of removal by erosion. Typical sites for deposition include flood and ebb deltas near the mouth, navigation channels, the region of maximum turbidity, harbors, and small basins (Ippen 1966; Mehta et al. 1982).

b. In the absence of significant and rapid natural or man-made changes, estuaries tend to be in a state of quasi-equilibrium as far as the hydrodynamic and sedimentary processes are concerned. This means that, superimposed on the annual cycle of variation of tides, freshwater flows, salinity intrusion, and sediment transport, longer period variations in the physical regime occur. Slow filling up of the existing deep channel or thalweg, coupled with scouring of a new channel elsewhere, may occur over a 10- to 20-year period, as, for example, occurs near the mouth of the Hooghly Estuary in India (Calcutta Port Commissioners 1973; McDowell and O'Connor 1977). Many estuaries are slowly filling with sediments. It is therefore critically important to understand the long-term estuarial behavior through an adequate monitoring program, particularly one involving extensive bathymetric surveys.

D-9. Consolidation. Consolidation is the volume change in sediment material with time. The fully consolidated volumes of fine sediments are often only a fraction of their initial deposited volumes. Coarse sediments do not consolidate under estuarine conditions; the discussion that follows deals with fine or cohesive sediments. Consolidation should be considered under the following circumstances: when evaluating sediment dispersal resulting from dredging or originating from a disposal site; when sizing confined or unconfined disposal areas for dredged materials; or when calculating dredging volumes or masses.

a. The formation of fluid muds can alter the transport mode of fine-grained sediments and therefore can be important to sediment transport and shoaling analyses. Fine-grained material with high moisture or low bulk density has relatively low shear strength, and can flow under the effects of gravity or the overlying flow. Observations of fluid mud flow have been made using radiotracers. The consolidation processes of stationary fluid mud are important to bed hydraulic shear strength and to net deposition in tidal flows. Where the thickness of fluid mud layers becomes substantial (say a foot or more), it is often referred to as "fluff." Such fluid mud layers often collect in navigation channels and can achieve thicknesses of several feet, as in the Savannah Estuary (Krone 1972). Fluid mud layers have acoustic properties resembling consolidated sediments even though they do not impede navigation. It is likely that large sums of money have been expanded to "remove" fluid mud layers. Better rapid bottom characterization techniques are needed and are currently being investigated in the Dredging Research Program at WES. Consolidation affects the ultimate volume and rate of volume change in fine-grained dredged material.

b. The amount of consolidation that disposed dredged material will undergo can be predicted by settling tube or accelerated consolidation tests and models. Reference should be made to Montgomery (1978) or to Cargill (1983 and 1985). Dredged material can be observed in large laboratory columns for a month or more to determine its final settled condition, as one method of testing. Similar zone- or column-settling tests can be performed on finegrained sediments to determine settling characteristics over a range of high suspension concentrations. Tests are performed by making serial dilutions of sediments with native water and observing settling behavior in smaller clear jars or columns. Once the relationship between concentration and settling rate is determined, further analyses can be made. By plotting settling rate versus concentration on log-log paper, the concentration at which sediments begin to behave as a deposit and how quickly concentration and strength increases can be identified. If self-weight consolidation modeling is to be carried out, special controlled-strain consolidation testing is required. Controlled-strain consolidation testing is performed at the WES Geotechnical Laboratory.

D-10. Physical Models. Physical hydraulic models are scaled representations of the prototype. They are adjusted to reproduce the important characteristics of estuarine flow. Physical hydraulic models can be important tools in sedimentation analysis of estuaries, including sedimentation patterns. Physical hydraulic modeling should be considered as one component of a program to study sedimentation if three-dimensional flow effects are known or suspected to be important. Chapter 3 described their use in hydrodynamic evaluations. Much of the physical modeling of estuaries in the United States is performed at the WES Hydraulics Laboratory and a compilation is provided in Appendix F. This section will briefly describe the use of physical hydraulic models in sedimentation studies.

a. Scales. Scale modeling of sediment transport is difficult because of scale effects and conflicting scaling requirements for the various important processes. For noncohesive sediments, compromises in scaling requirements can usually be devised by setting the time scale empirically, but considerable modeling skill is required to conduct and interpret the tests. For cohesive sediments, scale modeling is made even more difficult by the inability to scale down sediment aggregation and settling velocity. The most common practice has been to use noncohesive model sediments as tracers and apply considerable intuition and judgment to the results before drawing conclusions.

b. Processes. Physical hydraulic models are three-dimensional representations of the prototype system and have been successfully used to predict tidal currents, circulation, riverflows, salinity distributions, and dispersion processes. Many or all of these processes influence sedimentation. The ability of physical models to represent the flows in complex geometry makes them useful tools. Physical hydraulic models have been successfully incorporated into hybrid model studies as discussed in Paragraph D-13. Because they are real, physical representations, physical hydraulic models display system dynamics in a manner that can be readily assimilated by both modeler and lay persons. The initial cost for a physical hydraulic model is somewhat higher than for other methods, but they can be operated and maintained for years and serve many studies over their lifetime. Physical hydraulic models can simulate long periods of time, spring-to-neap cycles, or hydrographs.

c. Test Procedures. During model verification, hydraulic and salinity adjustments are made first. Sedimentation is adjusted to shoaling volumes computed from a series of prototype hydrographic surveys. Methods are developed developed during model adjustment to introduce, distribute, and collect model sediments. Sedimentation rates are often scaled against maximum or total values. A base test is sometimes performed, but often the verification tests serve this purpose. Plan tests are then run to assess the impacts of the test modifications on sedimentation. Model sediment tracers are commonly used in fixed-bed physical models to trace the paths that eroded material will follow and to develop shoaling distribution changes caused by estuarine modifications.

D-11. Analytical Models. Analytical models are closed-form mathematical solutions for sediment transport rate of deposition. Data required to "drive" analytical models come from field surveys, another model, or assumed conditions. Analytical models are considerable simplifications of estuarine sedimentation processes but are useful for such tasks as screening, checking the reasonableness of other methods, and identifying important processes. The following are some examples of analytical models.

a. Treatment of Data. Analytical models are a method of treating prototype data. Time series velocities and concentrations can be integrated using assumed critical shear stresses to estimate depositional flux or net deposition. Equations such as D-4 or D-7 can be used for this purpose and form the basis for a closed-form mathematical solution.

b. Interpretation of Field Data. First, currents are used to calculate bed shear stress τ_b using Manning's or some other expression. Note that only an approximate estimate of shear stress can be expected from such a procedure. Using a critical shear stress for deposition (τ_{cd} ~ 0 to 0.15 Newtons per square metre), deposition probabilities P are calculated over the portion of the data when $\tau_b < \tau_{cd}$ where

$$P = 1 - \frac{\tau_b}{\tau_{cd}} \; ; \; \tau_b < \tau_{cd} \qquad \text{(D-8)}$$

as described in Equation D-5. The product PW_sC_b is integrated over that portion of the tide curve, where C_b is the near-bed concentration. Erosion is estimated by integrating $M[(\tau_b/\tau_s) - 1]$ over that portion of the tide curves when bed shear stress is greater than the threshold value for bed erosion τ_s as in Equation D-7. The rate constant M has been reported to be from 0.0002 to 0.0020 kilograms per square metre per second (Hunt 1981). Deposition and erosion can then be summed to a net bed change value.

c. Flux Analysis. An alternate or supplemental analysis to that of the last section is horizontal suspended flux analysis using prototype data. Flux is the movement of material and has the units of mass per time. Horizontal flux analysis makes no assumption about deposition characteristics of sediments. Deposition or erosion can be inferred from longitudinal gradients of sediment flux using this method. Inglis and Allen (1957) presented examples and methods for computation. Measurements of currents, salinities, and suspended sediment concentration over depth and over a tidal cycle can be used to calculate the total fluxes at a station by integration over time and space (Teeter 1988). More information can be obtained from the data by decomposing sediment and salinity fluxes to identify dominant transport processes, as described in D-11e.

d. Suspended Concentration Analysis. A useful approach to the analysis of data collected over a tidal cycle, and at several depths and stations, is to reduce the data to a small number of parameters that represent important transport information (Teeter 1989). Sediment concentration, as well as velocity and salinity, data can be so reduced by a series of spatial and temporal averagings into a combination of tidal-mean and fluctuating depthmean components, as well as vertical deviations from the depth-means. For example, at some time t and station depth z, an individual datum of suspended sediment concentration C can be decomposed into components thus:

$$C(z,t) = Co + Cov(z) + Ci'(t) + Civ'(z,t) \tag{D-9}$$

where $\bar{C}o$ is the depth-averaged tidal-mean concentration, $Cov(z)$ is the vertical deviation of the tidal mean from the depth mean, $Ci'(t)$ is the depth mean instantaneous concentration component, and $Civ'(z,t)$ is the vertical deviation of the instantaneous component from the depth mean. Then by root-mean-square averaging in the remaining dimensions four components are formed. They include the depth-averaged time-mean concentration, Co, the vertical deviation from the depth mean, Cov, the depth-averaged fluctuating component, Ci, and the depth deviation in the fluctuating component, Civ. A similar approach can be used to examine lateral variations in transport.

e. Sediment Flux Components. More information on the processes responsible for estuarine suspended sediment transport can be obtained by decomposing fluxes into components. Multiplying suspended sediment concentrations by velocities and decomposing the resulting fluxes into components, as described earlier for sediment concentration, identify the relative magnitude of important processes or mechanisms including transport by net flow, vertical circulation, and tidal pumping. Net flows result from freshwater flows, from long-period (subtidal) oscillations, and from tidal asymmetry. Transport by vertical circulation (vertical shear in the mean flow) is often associated with density effects in estuaries. Vertical circulation is usually at least partially responsible for the maintenance of turbidity maximums and for high--shoaling rates in estuarine mixing zones. Tidal pumping is an advective transport process that operates in the direction of reduced concentrations. For instance, if overall suspended sediment concentrations are higher on the flood than on the ebb tide, transport by depth mean tidal pumping in the upstream direction is indicated. Further, if near-bed suspended sediment concentrations are higher on the flood than on the ebb tide (typical), and/or if the near-bed velocities are higher on the flood than on the ebb tide (also typical), transport by tidal pumping at depth is indicated. Decompose tidal-cycle suspended sediment fluxes into components or correlations thus:

$$\text{Flux of } C = A(\bar{U}o\bar{C}o + \overline{UiCi} + \overline{UovCov} + \overline{UivCiv}) \tag{D-10}$$

where A is cross-sectional area at the sampling point. $\bar{U}o\bar{C}o$ is the product of depth and time mean values of velocity and concentration and represents sediment transport by depth-mean residual flows. $\overline{UiCi}$ is the correlation between depth-mean velocity and sediment concentration fluctuation $\overline{UovCov}$ is the transport associated with steady vertical shear and concentration deviations. $\overline{UivCiv}$ represents transport by correlations between fluctuations in velocity and concentration deviations. $\overline{UiCi}$ and $\overline{UivCiv}$ comprise tidal pumping. The first two terms on the right-hand side of Equation D-10 are depth mean, and the last two arise from vertical effects and circulation. Similar analyses can be carried out for the lateral direction.

f. Depositional Models. Zero-dimensional (in the spatial domain) models can be applied to basins or to channels with relatively steady and uniform flows. A slightly more complex model incorporating tidal prism input could be applied to an estuary as a whole or to tidal basins. A starting point for one such model is the depth- and tidal-averaged deposition equation for fine sediments:

$$H \frac{dC}{dt} = \gamma \frac{dH}{dt} = - \Sigma_i P_i W_{si} C_{bi} \tag{D-11}$$

where H is depth and γ is the unit weight of the bed sediments. The subscript i indicates a settling class of sediments. The solution for this equation for a single component or class after substitution of an expression relating near-bottom to depth-mean concentration is

$$\frac{C}{C_o} = \exp\left\{ -tPW_s \left[\frac{1}{H} + \frac{W_s}{K_z(1.25 + 4.75P^{5/2})} \right] \right\} \tag{D-12}$$

where C and C_O are the depth mean and initial or inflow depth mean concentrations, respectively, and K_Z is the depth-averaged vertical diffusivity. The last term in this expression vanishes as the suspension becomes more vertically well-mixed.

D-12. Numerical Models. Most numerical modeling of estuaries and estuarine sedimentation within the US Army Corps of Engineers is done at the WES Hydraulics Laboratory. A variety of one-, two-, and three-dimensional models have been applied. Multidimensional unsteady numerical models for sediment transport began to be developed in the mid-1970's. A two-dimensional (in the horizontal plane) numerical sedimentation model is included in the Corps' TABS-2 modeling system (Thomas and McAnally 1985). TABS-2 is available to qualified users Corps-wide. Training on the TABS system is available at WES. An example numerical modeling investigation including sediment transport (using the two-dimensional, laterally averaged model LAEMSED) is given in Appendix C.

a. Model Processes. Numerical sediment models are transport models with nonconservative bed interaction terms. Sediments are numerically transported by advective currents and by diffusion. Sediment models require that currents be supplied by a hydrodynamic (usually numerical) model. Interactions between suspended sediments and the bed are governed by process equations in sediment transport models. Coarse sediment-bed interaction terms usually depend on the difference between sediment in transport and the competency of the flow to transport material. Fine sediment-bed interaction terms consist of process description for erosion and deposition similar to Equations D-4 and D-7. Bed structure or layering is usually modeled in some way to account for changes in density and shear strength with depth in fine sediments (Teeter and Pankow 1989c). Numerical sediment models are classified by their dimensions, by sediment type, and the equations that are solved.

b. Model Applications. Numerical models are the most advanced modeling method available for simulating sedimentation. Numerical models in general are limited to two dimensions, although three-dimensional models are currently (1989) under development and testing. Even so, numerical models contain vastly less geometric information than, say, a physical model. Also, the equations solved by numerical hydrodynamic and sediment models are simplifications or abstractions of actual behavior. Analyses suggested earlier to analyze sediment flux can also be used as a guide to select model dimensions, especially the need to include the vertical dimension. Numerical modeling, like other modeling methods, remains an art-science and successful application to real problems depends heavily on the skill, experience, and intuition of the model user.

D-13. Hydrid Models. Combining two or more models in a solution method is hybrid modeling. Hybrid models attempt to use the best modeling methods available available for each "part" of sedimentation problems: current structure and sediment transport. Hybrid sediment models or analyses use one modeling method for hydrodynamics and another method for the sediment predictions. The following are the most frequently used hybrid techniques, starting with the most rigorous.

a. Physical-Numerical. The physical-numerical hybrid modeling approach uses a physical model to predict currents and a numerical model to predict sediment transport. This approach has been successfully applied to a number of estuarine sediment problems at the WES Hydraulics Laboratory. Since current velocities are needed at a great many points for the numerical sediment model, a numerical hydrodynamic model is employed as an "interpolator" of the physical model results. The physical model can be used to generate boundary conditions for the detailed numerical mesh or grid of the sediment model.

b. Physical-Analytical. The physical-analytical hybrid modeling approach uses a physical model for currents and an analytical model to predict sedimentation. Velocities can be collected at various points in the physical model and converted to bed shear stress histories. Dye study results can also give indications of circulation and residence times between various areas. Physical model results can then be extended using appropriate analytical expressions such as Equations D-4 and D-7. Only limited spatial coverage can be obtained with this technique, and simplifying assumptions must be made about the behavior of the sediments. This technique is useful when sedimentation is caused by some feature of the flow or of the residual circulation.

c. Numerical-Analytical. A numerical-analytical hybrid model uses a numerical model to predict hydrodynamics. Numerical hydrodynamic models are more costly to operate than numerical sediment models, but numerical sediment models can be significantly more costly to adjust and verify. The numerical-analytical hybrid technique avoids the costs associated with numerical sediment modeling, but at the expense of considerable rigorousness. The results from a hydrodynamic model can be used to address limited questions on sedimentation using analytical models. The shear stress at various points can be evaluated to predict deposition or erosion. Circulation and sources of sediments cannot be addressed. The analytical method can be applied only to a relatively small number of locations.

D-14. Field Data Requirements. All analyses depend on field data. Field data acquisition may be the most costly part of a sedimentation study. Required data can be grouped into system definition and behavior and boundary data. System definition includes the topography, sediment characteristics, and water level statistics. System behavior includes both synoptic tidal propagation, current structure, suspended sediment concentrations, and salinities and/or long-term records of water levels, currents, suspended sediment concentrations, salinities, and shoaling volumes. An evaluation should be made of the importance of meteorologic or hydrologic events, requiring records or samplings over an appropriate span of time. Boundary data includes freshwater inflows to the system, tidal information, and all other modeled state variables (salinity, sediment concentration, etc.) at the boundaries of the system (see Chapter 3). The following discussion is limited to sediment data requirements.

a. A good way to determine system behavior is to conduct a boat survey in which currents, salinities, and suspended sediment concentrations are collected at short time intervals (half hour) at several stations across several cross sections over at least one tidal cycle. Normally about two to five samples in the vertical are sufficient in depths of 50 feet or less. A greater number may be required in deeper water. Onsite determinations of settling velocity should be made at strengths of flow and possibly slack waters. If suspension concentrations are high (>~1,000 mg/ℓ), vertical sampling resolution should be increased to ~2 metres or supplemented by continuous continuous turbidity or light transmittance profiles. Tides at several locations and supporting measurements or observations of winds or other factors are also required. If an intensive boat survey is not possible, fewer points can be sampled over longer (weeks) time periods, perhaps using automated equipment. Sampling at the boundaries of the area to be modeled is particularly important.

b. Bed sediment properties are required for system definition. Methods for sediment characterization were described in Paragraph D-6. Settling experiments in the field are preferred to laboratory tests, although conditions may require the latter. It is usually not practical to carry out enough settling tests in the field to obtain sufficient spatial and temporal coverage. Supplemental information on settling can be obtained by the analysis of many vertical suspended sediment profiles and/or high-resolution non-dispersed particle size analysis (such as Coulter Counter analysis). Water column measurements of sediment concentration should include some measurements near or at the sediment bed-water interface. The presence of fluid mud should be checked using acoustic soundings, densimetric profiling, or low-disturbance coring devices. Shallow coring is also a good method of determining bed structures such as armoring, density differences, or layering.

c. It is very difficult to collect field data on all the important sediment properties. Classification by the methods described in earlier paragraphs may be useful in estimating sediment properties from existing data. Settling velocities, critical shear stresses for erosion and deposition, and the densities of fine-grained deposited material are properties that might require supplemental laboratory study. A series of laboratory settling tests on bed sediments should be run over a range of concentrations typical of the prototype to characterize this relationship. Further discussion on field data requirements for sediment transport modeling is given in Appendix B.

D-15. Notation. For the reader's convenience, notation used in Chapter 4 and Appendix D is listed here. Typical units have been included and are dependent upon the equation in which used.

A = Cross-sectional area at the sampling point, m^2

C = Suspension concentration, mg/ℓ or gm/m^3

C_b = Near-bed concentration, mg/ℓ

$Ci'(t)$ = Depth mean instantaneous concentration component

$Civ'(z,t)$ = Vertical deviation of the instantaneous component from the depth mean

C_o = Initial or inflow depth mean concentration, mg/ℓ

$C_{ov(z)}$ = Vertical deviation of the tidal mean from the depth mean

$\bar{C}$ = Depth-averaged suspension concentration, mg/ℓ

$\bar{C}_o$ = Depth-averaged initial tidal mean concentration, mg/ℓ

d = Grain size, m, mm, or μm

d_{gr} = Dimensionless grain size

g = Acceleration due to gravity, m/sec^2

H = Depth, m

K_z = Depth-averaged vertical diffusivity, m^2/sec

m = Mass of suspended sediment per unit bed area over the depth of flow, (Kg - m^2)/m

M = Empirical erosion rate constant, kg/m^2/sec

P = Deposition probability, nondimensional

SAR = Sodium absorption ratio

t = Time, sec or min

u_* = Friction velocity, mm/sec

$\overline{UiCi}$ = Correlation between depth mean velocity and sediment concentration fluctuations

$\overline{UivCiv}$ = Transport by correlations between fluctuations in velocity and concentration deviations

$\bar{U}o\bar{C}o$ = Product of depth and time mean values of velocity and concentration and represents sediment transport by depth-mean residual flows

$\overline{UovCov}$ = Transport associated with steady vertical shear and concentration deviations

W_s = Settling velocity, cm/sec or m/sec

z = Station depth, m

γ = Unit weight of water, g/ℓ or kg/m^3

γ_s = Unit weight of sediment, g/ℓ or kg/m^3

Θ = Entrainment function

Θ_{cri} = Critical value of the entrainment function

Θ_{crs} = Critical value for sediment suspension

ν = Kinematic viscosity of fluid, m^2/sec

ρ = Dry density, g/ℓ or kg/m^3

τ_b = Bed shear stress, N/m^2

τ_{cd} = Critical shear stress for deposition, N/m2

τ_s = Critical shear stress for erosion, N/m^2